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THE TEMPORAL DEPENDENCE OF ADHESION JOINING STRENGTH: THE DIFFUSIVE MODEL

Key words: polystyrene, adhesion, strength, fractal analysis, anomalous diffusion.

The quantitative model of the dependence of adhesion contact shear strength on its formation duration was proposed, which uses fractal analysis and strange (anomalous) diffusion notions. This model gives a clear physical picture of contact formation and allows precise enough estimations of adhesion joining strength.

Ключевые слова: полистирол, адгезионная прочность, фрактальный анализ, аномальная диффузия.

Предложена количественная модель зависимости адгезионной прочности от времени формирования контакта с использованием рекурсивного анализа и аномальной диффузии. Эта модель дает четкую физическую картину формирования контакта и позволяет достаточно точно оценить адгезионные характеристики.

1. Introduction

At present the general law – governed nature is well-known: adhesional contact formation duration increasing at other equal conditions results in its strength enhancement [1, 2]. As a rule, this effect is explained by macromolecular coils diffusion in boundary layer of samples, forming adhesional contact [3]. However, such explanation has usually a qualitative character. Therefore the present work purpose is the development of the quantitative model adhesional contact strength temporal dependence. Within the frameworks of fractal analysis and anomalous (strange) diffusion conception on the example of amorphous polymer – polystyrene (PS) [1].

2. Experimental

Amorphous PS ($M_w=23 \times 10^4$, $M_w/M_n=2.84$), obtained from Dow Chemical (USA) was used. The glass transition temperature T_g was measured using Perkin-Elmer DSC-4 differential scanning calorimeter, at a heating rate of 20 K/min ($T_g=376$ K for PS) [2]. For adhesional joinings formation two samples with width of 5 mm were bonded in a lap-shear joint geometry with the area of $5 \times 5 \text{ mm}^2$, using a Carver laboratory press at constant temperature and pressure of 0.8 MPa. Division boundaries PS-PS were healed during 10 min and 24 h within the range of temperatures of 335–373 K – in all cases below glass transition temperature. Mechanical tests of the formed contacts were conducted at temperature 293 K on an Instron tensile tester, Model 1130 at tension rate of 3×10^{-2} m/s with shear strength determination in the contact zone (or on division boundary) [1, 2].

3. Results and Discussion

As it is known [4], within the frameworks of fractal analysis shear strength τ_c of adhesional joining is described by the following general equation:

$$\ln \tau_c = A \ln N_c - B, \quad (1)$$

where A and B are constants, which can be changed depending on polymer nature, temperature, testing specific conditions and so on, N_c is macromolecular coils contacts number, which is determined as follows [5]:

$$N_c \sim R_g^{D_{f1}+D_{f2}-d}, \quad (2)$$

where R_g is a macromolecular coil gyration radius, D_{f1} and D_{f2} are fractal dimensions of the coils structure,

forming autohesional bonding, d is dimension of Euclidean space, in which a fractal is considered (it is obvious, that in our case $d=3$).

For the autohesion case $D_{f1}=D_{f2}=D_f$ and $d=3$ the equation (2) is simplified up to:

$$N_c \sim R_g^{2D_f-3}. \quad (3)$$

Let us consider estimation methods of the parameters, included in the equation (3), i.e. D_f and R_g . For the dimension D_f estimation the following approximated technique will be used, which consists in the following. As it is known [7], between D_f and structure dimension d_f of linear polymers in the solid state the following intercommunication exists:

$$D_f = \frac{d_f}{1.5}. \quad (4)$$

d_f estimation can be conducted according to the formula [6]:

$$d_f = 3 - 6 \left(\frac{\Phi_{cl}}{SC_\infty} \right)^{1/2}, \quad (5)$$

where Φ_{cl} is a relative fraction of local order domains (clusters), S is a macromolecule cross-sectional area, C_∞ is characteristic ratio, which is an indicator of polymer chain statistical flexibility [8].

Φ_{cl} value was estimated according to the following percolation relationship [6]:

$$\Phi_{cl} = 0.03(T_g - T)^{0.55}, \quad (6)$$

where T_g and T are temperatures of glass transition and autohesional contact formation, respectively.

For PS $C_\infty=9.8$ [9], $S=54.8 \text{ \AA}^2$ [10]. Further the macromolecular coil gyration radius R_g was calculated as follows [11]:

$$R_g = l_0 \left(\frac{C_\infty M_w}{6m_0} \right)^{1/2}, \quad (7)$$

where l_0 is the length of the main chain skeletal bond, which is equal to 0.154 nm for PS [9], m_0 is the molar mass per backbone bond, which is equal to 52 for PS [11].

Let us note the important methodological aspect. At R_g value calculation according to the equation

(7) value C_∞ was accepted as a variable one and calculated according to the following equation [6]:

$$C_\infty = \frac{2d_f}{d(d-1)(d-d_f)} + \frac{4}{3}. \quad (8)$$

The constants A and B in the equation (1) for PS are equal to 2.15 and 6.0, respectively [12].

As it is known [11], at $M_w > 12M_e$ (where M_e is molecular weight of a chain part between macromolecular entanglements) the boundary layer thickness α_i in the autohesion case can be determined according to the formula [11]:

$$\alpha_i = l_0 \left(\frac{12C_\infty M_e}{6m_0} \right)^{1/2}. \quad (9)$$

In PS case $M_e = 18000$ [11], i.e. the indicated above condition $M_w > 12M_e$ is fulfilled and the equation (9) can be used for α_i value estimation. In Fig. 1 the comparison of macromolecular coil gyration radius R_g , calculated according to the equation (7), and the boundary layer thickness α_i , calculated according to the formula (9), is adduced. As one can see, at contact formation duration $t = 10$ min α_i value reaches R_g value in PS case. Let us also note, that the equation (9) does not assume α_i dependence on contact formation duration t , although the dependence $\tau_c(t)$ exists [1]. This circumstance provides boundary layer structure change for autohesional joining at $t > 10$ min.

In Fig. 2 the comparison of experimental τ_c and calculated according to the equation (1) τ_c^T autohesional joining PS-PS shear strength values at the indicated above conditions is adduced. As one can see, if for $t = 10$ min the theory and experiment good correspondence is observed, then for $t = 24$ hours such correspondence is absent – the values τ_c^T are essentially smaller than the experimentally obtained ones. As it was noted above, this effect was due to boundary layer structure change in virtue of proceeding in it macromolecular coils diffusion processes. Let us consider the indicated processes within the frameworks of anomalous (strange) diffusion conception [13].

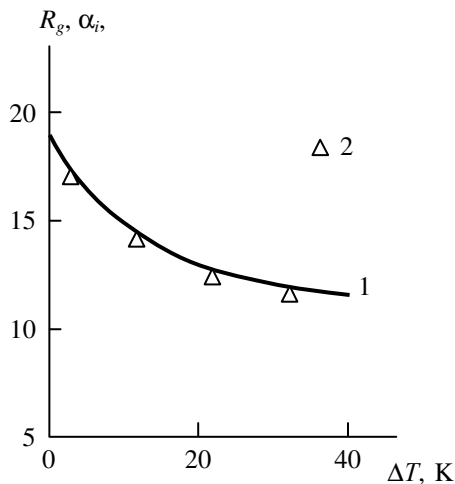


Fig. 1 - The dependences of macromolecular coil gyration radius R_g (1) and boundary layer thickness α_i (2) on autohesional joining glass transition and formation temperatures difference $\Delta T = T_g - T$ for PS

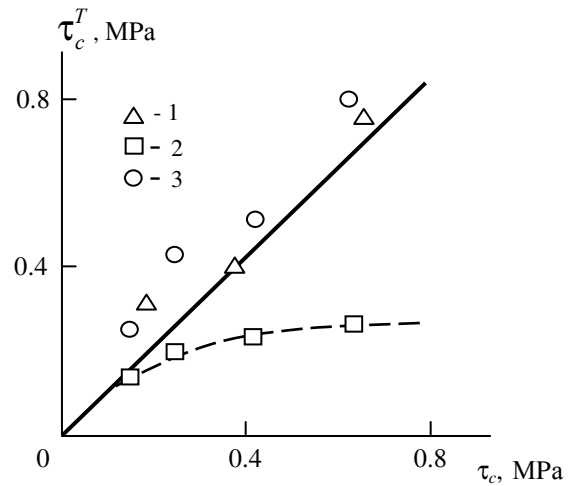


Fig. 2 - The comparison of experimental τ_c and calculated according to the equation (1) τ_c^T shear strength values of autohesional joining for PS. The joining formation duration $t = 10$ min (1) and 24 hours (2, 3). The calculation of dimension d_f according to the equation (5) (1, 2) and (13) (3)

The basic equation of this conception can be written as follows [14]:

$$\langle r^2(t) \rangle^{1/2} = D_{gen} t^\beta, \quad (10)$$

where $\langle r^2(t) \rangle^{1/2}$ is mean-square displacement of a diffusible particle (the size of region, visited by this particle), D_{gen} is generalized diffusivity, β is diffusion exponent. For the classical case $\beta = 1/2$, for the slow diffusion - $\beta < 1/2$ and for the fast one - $\beta > 1/2$. The condition $\beta \neq 1/2$ is the definition of anomalous (strange) diffusion.

The border value for slow and fast diffusion processes is the condition $d_f = 2.5$ [13]. Since for the considered in the present work PS samples $d_f \geq 2.88$, then all proceeding in them diffusion processes are slow ones. The exponent β value is connected with the main parameter in a fractional derivatives theory (fractional exponent α) by the following relationship [13]:

$$\beta = \frac{1-\alpha}{2}. \quad (11)$$

In its turn, the fractional exponent α is determined according to the equation [13]:

$$\alpha = d_f - (d-1). \quad (12)$$

The equations (11) and (12) combination allows to obtain direct interconnection between rate (intensity) of diffusive processes in the autohesional joining border layer, characterized by exponent β , and the polymer structure, characterized by dimension d_f :

$$\beta = \frac{d-d_f}{2}. \quad (13)$$

It is obvious, that in the autohesion case the value $\langle r^2(t) \rangle^{1/2}$ will be equal to α_i and then generalized diffusivity D_{gen} at $t = 10$ min in relative units according to the equation (10) can be determined. Further the exponent β for $t = 24$ hours can be determined according to the same equation and the dimension d_f of boundary layer structure for the same conditions from the equa-

tion (13) can be calculated. In Fig. 3 the dependence of D_{gen} on autoheshional contact formation temperature T for PS is adduced. As it was to be expected from the most common considerations [13, 14], D_{gen} increasing at T growth is observed.

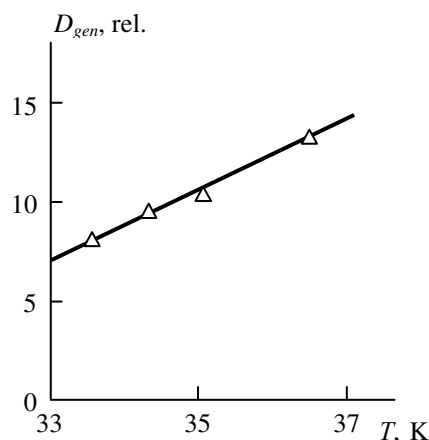


Fig. 3 - The dependence of generalized diffusivity D_{gen} on autoheshional joining formation temperature T for PS

Let us note, that the obtained according to the equation (13) d_f values for $t=24$ hours proved to be higher than a the ones calculated according to the equation (5) ($d_f=2.931-2.950$ and $d_f=2.878-2.914$, respectively), that was expected. Then with the described above technique usage (the equations (1), (3), (4) and (13)) the values of autoheshional contact shear strength τ_c^T were calculated, the comparison of which with the corresponding experimental values τ_c is adduced in Fig. 2. As one can see, the consideration of autoheshional joining boundary layer structure change, which is due to the proceeding in it macromolecular coils anomalous (strange) diffusion processes allows to improve essentially the theory and experiment correspondence. But the main merit of the proposed model is a clear physical picture of autoheshional joining shear strength temporal dependence causes.

4. Conclusions

In the present paper the quantitative model of the autoheshional joining shear strength dependence on

its formation duration was proposed. This model uses notions of fractal analysis and anomalous (strange) diffusion conception. The indicated model application gives a clear physical picture of the observed effect: the obtained experimentally shear strength enhancement is due to boundary layer structure change owing to macromolecular coils diffusion. This model allows also precise enough estimations of autoheshional joining strength.

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